Amendments to the Claims

This Listing of Claims replaces all prior versions, and listings, of claims in the present application.

Listing of Claims

1. (previously presented) A hydrogen storage and delivery system comprising a liquid hydrogen storage vessel in the shape of a hollow toroid having an interior surface that defines a hydrogen storage volume of the storage vessel, substantially vertically oriented orifice pulse tube refrigerator extending in a void space that is defined by said toroidal storage vessel and is located at the geometric center thereof, and a cooling system coupled to the orifice pulse tube refrigerator, said cooling system being adapted to counteract or abate heat transfer to the storage vessel from the ambient environment, and wherein no cold heat exchanger of said orifice pulse tube refrigerator penetrates the liquid hydrogen storage vessel.

2. (canceled)

3. (previously presented) The system according to claim 1, said cooling system comprising a first thermal jacket exterior to and substantially enclosing said storage vessel, and a second thermal jacket exterior to and substantially enclosing said first thermal jacket.

4. (previously presented) The system according to claim 3, said cooling system further comprising a super insulation material disposed around and substantially enclosing at least said storage vessel and said first thermal jacket.

5. (previously presented) The system according to claim 3, said orifice pulse tube refrigerator comprising a first stage orifice pulse tube refrigeration unit and a second stage orifice pulse tube refrigeration unit that operates at a lower temperature than the first stage refrigeration unit, said first stage refrigeration unit being thermally coupled to said second thermal jacket, and said second stage refrigeration unit being thermally coupled to said first thermal jacket.

6. (previously presented) The system according to claim 5, said first stage refrigeration unit comprising a first stage cold heat exchanger having a first refrigerant fluid flow passage that is coupled to and in fluid communication with said second thermal jacket, said second stage refrigeration unit comprising a second stage cold heat exchanger having a second refrigerant fluid flow passage that is coupled to and in fluid communication with said first thermal jacket,

wherein a first refrigerant fluid, refrigerated at said first stage cold heat exchanger to a first temperature, is circulated through said second thermal jacket during operation of said system,

and wherein a second refrigerant fluid, refrigerated at said second stage cold heat exchanger to a second temperature, is circulated through said first thermal jacket during operation of said system.

7. (previously presented) The system according to claim 6, said first temperature being 60-100K.

8. (previously presented) The system according to claim 6, said second temperature being 13-20K.

9. (previously presented) The system according to claim 1, said cooling system comprising a heat transfer body projecting directly into a hydrogen storage volume of said storage vessel, said heat transfer body being thermally coupled to said orifice pulse tube refrigerator.

10. (previously presented) The system according to claim 9, said heat transfer body comprising a heat transfer fin.

11. (previously presented) The system according to claim 1, further comprising an oscillatory gas pressure power source coupled to said orifice pulse tube refrigerator via a transfer tube,

said orifice pulse tube refrigerator comprising a first stage orifice pulse tube refrigeration unit and a second stage orifice pulse tube refrigeration unit, each of the first and second stage refrigeration units comprising a respective regenerator, cold heat exchanger, pulse tube, hot heat exchanger, primary orifice, inertance tube, and reservoir volume,

each of the first and second stage refrigeration units further comprising a secondary orifice connecting the respective hot heat exchanger to the transfer tube.

12. (currently amended) The system according to claim [[2]] 1, said cooling system comprising a first thermal jacket in the shape of a toroid located concentrically adjacent and substantially enclosing the liquid hydrogen storage vessel.

13. (previously presented) The system according to claim 12, said first thermal jacket comprising a length of tubing coiled in the shape of a toroid around the storage vessel and adapted to accommodate a flow of a first refrigerant fluid therethrough.

14. (previously presented) The system according to claim 13, said tubing having at least one flat side extending longitudinally along the tubing's outer surface, said tubing being wound around said storage vessel such that said flat side of said tubing is in direct contact with said storage vessel.

15. (previously presented) The system according to claim 13, said tubing of said first thermal jacket being soldered or brazed directly to said storage vessel.

16. (previously presented) The system according to claim 12, said first thermal jacket being in fluid communication with a refrigerant fluid flow passage of said orifice pulse tube refrigerator for circulating a first refrigerant fluid, refrigerated by said orifice pulse tube refrigerator, through said first thermal jacket.

17. (previously presented) The system according to claim 12, said cooling system further comprising a second thermal jacket in the shape of a toroid located concentrically adjacent and substantially enclosing said first thermal jacket.

18. (previously presented) The system according to claim 17, said second thermal jacket comprising a length of tubing coiled in the shape of a toroid and adapted to accommodate a flow of a second refrigerant fluid therethrough.

19. (previously presented) The system according to claim 17, said orifice pulse tube refrigerator comprising a first stage orifice pulse tube refrigeration unit and a second stage orifice pulse tube refrigeration unit that operates at a lower temperature than the first stage refrigeration unit,

said second thermal jacket being in fluid communication with a first refrigerant fluid flow passage of said first stage refrigeration unit for circulating a first refrigerant fluid, refrigerated by said first stage refrigeration unit, through said second thermal jacket,

said first thermal jacket being in fluid communication with a second refrigerant fluid flow passage of said second stage refrigeration unit for circulating a second refrigerant fluid, refrigerated by said second stage refrigeration unit, through said first thermal jacket.

20. (previously presented) The system according to claim 19, said first refrigerant fluid flow passage being located in a first stage cold heat exchanger of said first stage refrigeration unit, and said second refrigerant fluid flow passage being located in a second stage cold heat exchanger of said second stage refrigeration unit.

21. (previously presented) The system according to claim 17, said cooling system further comprising super insulation material disposed around and substantially enclosing said storage vessel and said first thermal jacket, said second thermal jacket being provided or embedded within, or between adjacent layers of, said super insulation material.

22. (canceled)

23. (previously presented) The system according to claim 1, further comprising an outer housing defining a primary vacuum chamber therein, said liquid hydrogen storage vessel and said cooling system being disposed within said primary vacuum chamber.

24. (previously presented) The system according to claim 23, wherein operative cold components of said orifice pulse tube refrigeration unit are disposed within said primary vacuum chamber.

25. (previously presented) The system according to claim 23, said primary vacuum chamber being maintained at about or less than 10^{-4} torr.

26. (previously presented) The system according to claim 23, said housing further defining a secondary chamber, separate and apart from said primary vacuum chamber, said system further comprising relatively high temperature hydrogen conditioning equipment disposed within said secondary chamber.

27. (previously presented) The system according to claim 26, said secondary chamber being maintained under vacuum at about or less than 10^{-2} torr.

28. (previously presented) The system according to claim 26, said hydrogen conditioning equipment comprising a vaporizer coupled to said hydrogen storage vessel via a delivery pipe and adapted to receive liquid hydrogen therefrom, and a preheater coupled to said vaporizer and adapted to receive vaporized hydrogen therefrom, said preheater being further adapted to heat hydrogen gas vaporized in the vaporizer to a suitable temperature for delivery to a hydrogen-powered internal combustion engine or to a hydrogen-powered fuel cell.

29. (previously presented) The system according to claim 28, said delivery pipe being equipped with a liquid trap.

30. (previously presented) The system according to claim 1, said orifice pulse tube refrigerator comprising a first stage orifice pulse tube refrigeration unit and a second stage orifice pulse tube refrigeration unit that operates at a lower temperature than the first stage refrigeration unit, each of the first and second stage refrigeration units comprising a respective regenerator, cold heat exchanger, pulse tube and hot heat exchanger, said first stage regenerator having a first

heat absorptive material therein, said first heat absorptive material having a thermal conductivity not more than 28 W/m-K at 60-100K, a volumetric heat capacity of at least 1 J/cm^{3}K at 60-100K, and a porosity of at least 0.55.

31. (previously presented) The system according to claim 30, said first heat absorptive material being provided as a plurality of layers of stainless steel screen or mesh stacked axially or transversely within said first stage regenerator, said plurality of layers resulting in a pressure drop in said first regenerator not more than 1 psi.

32. (previously presented) The system according to claim 1, said orifice pulse tube refrigerator comprising a first stage orifice pulse tube refrigeration unit and a second stage orifice pulse tube refrigeration unit that operates at a lower temperature than the first stage refrigeration unit, each of the first and second stage refrigeration units comprising a respective regenerator, cold heat exchanger, pulse tube and hot heat exchanger, said second stage regenerator having a second heat absorptive material therein, said second heat absorptive material having a volumetric heat capacity of at least 0.23 J/cm^{3}K at 13-14K, a volumetric heat capacity of at least 0.5 J/cm^{3}K at 18-20K, and a porosity of 0.2-0.5.

33. (previously presented) The system according to claim 32, said second heat absorptive material being provided as a rare earth metal or rare earth metal compound.

34. (previously presented) The system according to claim 32, said second heat absorptive material being selected from the group consisting of erbium compounds.

35. (previously presented) The system according to claim 32, said second heat absorptive material being selected from the group consisting of erbium-praseodymium compounds.

36. (previously presented) The system according to claim 32, said second heat absorptive material being provided in the form of spheres having a mean diameter of 60-100 microns.

37. (currently amended) The system according to claim [[2]] 1, said orifice pulse tube refrigerator comprising a first stage orifice pulse tube refrigeration unit and a second stage orifice pulse tube refrigeration unit, each of the first and second stage refrigeration units comprising a respective regenerator, cold heat exchanger, pulse tube, hot heat exchanger, primary orifice, inertance tube, and reservoir volume,

wherein the first and second stage regenerators, cold heat exchangers and pulse tubes extend or are disposed within said void space defined by said toroidal storage vessel and located at the geometric center thereof.

38. (previously presented) The system according to claim 37, further comprising an outer housing defining a primary vacuum chamber therein,

said storage vessel and the first and second stage regenerators, cold heat exchangers and pulse tubes all being disposed within said primary vacuum chamber of said outer housing,

and the first and second stage hot heat exchangers, primary orifices, inertance tubes and reservoir volumes being disposed outside of said primary vacuum chamber.

39. (previously presented) The system according to claim 1, said system being effective to maintain liquid hydrogen in said storage vessel at or below 20K at steady state, such that substantially no venting of vaporized hydrogen is necessary to relieve hydrogen overpressure within the vessel.

40. (previously presented) The system according to claim 1, further comprising an oscillatory gas pressure power source coupled to said orifice pulse tube refrigerator, said oscillatory gas pressure power source being adapted to provide periodic pressure surges in a working fluid to drive said orifice pulse tube refrigerator to thereby generate refrigeration power.

41. (previously presented) The system according to claim 40, said oscillatory gas pressure power source being an electric gas compressor.

42. (previously presented) The system according to claim 41, said electric gas compressor being electric flexure bearing linear drive compressor.

43. (previously presented) The system according to claim 1, said orifice pulse tube refrigerator comprising a first stage orifice pulse tube refrigeration unit and a second stage orifice pulse tube refrigeration unit, each of the first and second stage refrigeration units comprising a respective regenerator, cold heat exchanger, pulse tube and hot heat exchanger,

wherein net refrigeration power for each of the first and second stage refrigeration units is generated respectively at the first stage cold heat exchanger and the second stage cold heat exchanger.

44. (previously presented) The system according to claim 43, said orifice pulse tube refrigerator being operable at steady state to generate 4-6 watts of refrigeration power with said first stage cold heat exchanger operating at 60-100K and said second stage cold heat exchanger operating at 13-20K.

45. (previously presented) An automobile comprising a hydrogen-powered internal combustion engine and/or a hydrogen-powered fuel cell, and a hydrogen storage and delivery system according to claim 1.

46. (original) A hydrogen storage and delivery system comprising a toroidal liquid hydrogen storage vessel, an orifice pulse tube refrigerator, and a cooling system,

said toroidal storage vessel having an interior surface defining a liquid hydrogen storage volume, said storage vessel further defining a void space located at the geometric center of the storage vessel,

said orifice pulse tube refrigerator extending within said void space at the geometric center of the storage vessel and comprising a first stage pulse tube refrigeration unit and a second stage pulse tube refrigeration unit, each of the first and second stage refrigeration units comprising a respective regenerator, cold heat exchanger, pulse tube and hot heat exchanger, wherein net refrigeration power for each of the first and second stage refrigeration units is generated at the respective first and second stage cold heat exchangers, and wherein the second stage cold heat exchanger operates at a lower temperature than the first stage cold heat exchanger,

said cooling system comprising a first thermal jacket in the shape of a toroid located concentrically adjacent and substantially enclosing the liquid hydrogen storage vessel, and a second thermal jacket in the shape of a toroid located concentrically adjacent and substantially enclosing the first thermal jacket.

47. (previously presented) The system according to claim 46, said first thermal jacket comprising a first length of tubing coiled in the shape of a toroid substantially enclosing the storage vessel and in fluid communication with a first refrigerant fluid flow passage thermally coupled to or located in the second stage cold heat exchanger, said second thermal jacket comprising a second length of tubing coiled in the shape of a toroid substantially enclosing the first thermal jacket and in fluid communication with a second refrigerant fluid flow passage thermally coupled to or located in the first stage cold heat exchanger.

48. (previously presented) The system according to claim 47, further comprising a super insulation material provided or wrapped around said storage vessel and said first thermal jacket, wherein said second thermal jacket is provided or embedded within, or in between adjacent layers of, said super insulation material.

49. (previously presented) The system according to claim 46, further comprising an outer housing defining a primary vacuum chamber therein, said storage vessel, cooling system, first and second stage regenerators, cold heat exchangers, pulse tubes and hot heat exchangers all being disposed within said primary vacuum chamber.

50. (previously presented) The system according to claim 49, said housing further defining a secondary chamber, separate and apart from said primary vacuum chamber, said system further comprising relatively high temperature hydrogen conditioning equipment located within said secondary chamber, said conditioning equipment being adapted at least to vaporize liquid hydrogen delivered thereto from said storage vessel, prior to delivering said hydrogen as a gas to a hydrogen-powered internal combustion engine or fuel cell.

51. (previously presented) The system according to claim 46, further comprising an electric flexure bearing linear drive compressor coupled to said orifice pulse tube refrigerator and adapted to provide periodic pressure surges in a working fluid to drive the orifice pulse tube refrigerator to thereby generate refrigeration power at said first and second stage cold heat exchangers.

52. (previously presented) The system according to claim 1, further comprising a liquid level sensing probe disposed within said storage vessel, said liquid level sensing probe comprising a plurality of adhered flexible dielectric strips and a series of temperature sensing units disposed at spaced intervals along the length of the probe, said probe remaining flexible at a temperature of 80K.

53. (previously presented) The system according to claim 46, further comprising a liquid level sensing probe disposed within said storage vessel, said liquid level sensing probe comprising a plurality of adhered flexible dielectric strips and a series of temperature sensing units disposed at spaced intervals along the length of the probe, said probe remaining flexible at a temperature of 80K.

54. (previously presented) The system according to claim 1, further comprising hydrogen conditioning equipment adapted to condition hydrogen drawn from said storage vessel to provide conditioned hydrogen in a suitable state for delivery to an engine or fuel cell that consumes said conditioned hydrogen as fuel.

55. (previously presented) The system according to claim 1, said storage vessel being adapted to deliver therefrom a metered quantity of hydrogen on demand for use as a fuel.